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Checked
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LBNE liquid argon cryostat

Find: the heat flux required to initiate pool boiling of liquid argon contained at 3psig.

$$q''_{\text{onb}} \approx 7.300 \text{ W/m}^2$$

References:

Barron, Randall F. *Cryogenic Heat Transfer*. (p. 161, 359, 363) Taylor & Francis, 1999.

Christensen, Jakob. *1-D Steady-State Neutronics Thermal-Hydraulics Model of a SWBR*. "Onset of Nucleate Boiling." Nikos Drakos 1993-1996, Ross Moore 1997-1998. Online version accessible at <http://www.jakobchr.com/project/node138.shtml>

Corradini, Michael L. *Fundamentals of Multiphase Flow*. "5.1. Bubble Nucleation and Onset of Nucleate Boiling." Last modified Sept. 1997. Online version accessible at <http://wins.engr.wisc.edu/teaching/mpfBook/node27.html>

Properties & Constants:

3psig = 122.009 kPa (absolute). This is the saturation pressure and relates to a saturation temperature of $T_{\text{SAT}} = 89.008\text{K}$. Properties of liquid argon shown below. Table data used for interpolation at T_{SAT} courtesy Barron, 1999.

| | Liquid Phase | | | Vapor Phase | | |
|-----------------------------------|--------------|-------------|---------|-------------|-------------|-------|
| T (K) | 87.28 | 89.00786748 | 90 | 87.28 | 89.00786748 | 90 |
| Density (kg/m ³) | 1393.9 | 1383.291402 | 1377.2 | 5.767 | 6.83421227 | 7.447 |
| C _p (kJ/kg-K) | 1.136 | 1.142987699 | 1.147 | 0.546 | 0.549811472 | 0.552 |
| μ (μPa/s) | 252 | 238.0246012 | 230 | 7.43 | 7.55704908 | 7.63 |
| k (mW/m-K) | 123.2 | 121.548362 | 120.6 | 5.48 | 5.594344172 | 5.66 |
| h _{fg} (kJ/kg) | 161.9 | 160.5659847 | 159.8 | | | |
| Pr | 2.32 | 2.237418098 | 2.19 | 0.74 | 0.742540982 | 0.744 |
| σ _L (mN/m) | 11.08 | 10.73061503 | 10.53 | | | |
| β _t (K ⁻¹) | 0.00433 | 0.004431639 | 0.00449 | | | |

v_{fg} 0.145599729

The natural convection regime occurs for temperatures given by:

$$\frac{C_L \Delta T}{h_{fg}} < (5 \times 10^{-5}) (Gr_b)^{0.2} (Pr_L)^{2.66} \quad (\text{Barron, 1999})$$

where $\Delta T \equiv T_w - T_{SAT}$

$$Gr_b = \frac{g \beta_L \rho_L^2 h_{fg}}{\mu_L^2 C_L} \left[\frac{\sigma_L}{g(\rho_L - \rho_v)} \right]^{3/2}$$

Calculating with our values for properties at T_{SAT} :

$$\begin{aligned} Gr_b &= \frac{(9.81)(4.432)(10^{-3})(1383.291)(160.566)^2}{((238.025)(10^{-4}))^2(1.143)} \\ &\quad \times \left[\frac{(10.73)(10^{-3})}{(9.81)(1383.291 - 6.834)} \right]^{3/2} \\ &= \frac{(1.33582)(10^7)}{(6.47577)(10^8)} \cdot \left[\frac{(10.73)(10^{-3})}{13,503} \right]^{3/2} \\ &\Rightarrow \boxed{Gr_b = 146,120} \end{aligned}$$

$$\Delta T = T_w - T_{SAT} < (5 \times 10^{-5}) (Gr_b)^{0.2} (Pr_L)^{2.66} \left(\frac{h_{fg}}{C_L} \right)$$

$$\begin{aligned} T_w &< (5 \times 10^{-5}) (Gr_b)^{0.2} (Pr_L)^{2.66} \left(\frac{h_{fg}}{C_L} \right) + T_{SAT} \quad \text{must be satisfied to prevent boiling.} \\ &< (5 \times 10^{-5}) (146,120)^{0.2} (2.237)^{2.66} \left(\frac{160.566}{1.143} \right) + 89.008 \end{aligned}$$

$$\Rightarrow \boxed{T_w < 89.6531 \text{ K}}$$

The onset of nucleate boiling ~~requires~~ is defined as

$$(T_w - T_{SAT})_{ONB} = \left[\frac{8 \cdot \sigma_L \cdot T_{SAT} \cdot g'' \cdot v_{fg}^2}{h_{fg} \cdot k_f} \right]^{1/2}$$

(Christensen
and Corradini)

where $v_{fg} = \frac{1}{\rho_g} - \frac{1}{\rho_f}$

therefore:

$$g''_{ONB} = \frac{\Delta T_{ONB}^2 \cdot h_{fg} \cdot k_f}{8 \cdot \sigma_L \cdot T_{SAT} \cdot v_{fg}^2}$$

$$= \frac{(0.645106)^2 (160.556)(121.548)(10^3)}{8(10.731)(10^{-3})(89.008)(0.1456)} = \frac{8.12201}{1.11255}$$

$$\Rightarrow \boxed{g''_{ONB} = 7.300 \text{ W/m}^2}$$

Nucleate boiling will occur
for heat fluxes $\geq g''_{ONB}$.

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[Next](#) [Up](#) [Previous](#) [Contents](#) [Index](#)
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[Go to Home](#)
[MS Research](#)
[PhD Research](#)
[Curriculum Vitae](#)

General:

[Linux](#)

Soon to come:

[Matlab](#)
[On-line Stores](#)
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[LaTeX](#)
[OOP & C++](#)
[Sony PCM-R500](#)
[DAT](#)

Onset of nucleate boiling

Since we have to detect when the boiling process start we need a requirement for the onset of nucleate boiling. The expression originally derived by Davis and Anderson has received a wide acceptance. Their requirement^{11.2} can be stated as

$$T_w - T_{\text{sat}} > \left[\frac{8\sigma_f T_{\text{sat}} q''_w v_{fg}}{h_{fg} k_f} \right]^{0.5} \quad (11.38)$$

where the specific volume v_{fg} [m^3/kg] is defined by

$$v_{fg} \triangleq \frac{1}{\rho_g} - \frac{1}{\rho_f} \quad (11.39)$$

and the properties are all evaluated at the saturation temperature.

If the wall temperature, T_w , calculated by utilizing (11.37) satisfies (11.38) we know that we have passed the point of onset of nucleate boiling and (11.37) is as a consequence insufficient for the evaluation of the convection heat transfer coefficient.

For explanatory reasons let us at this point disregard the subcooled boiling region (this subject is treated in section 11.2.4) and move directly to a description of saturated boiling heat transfer.

[Next](#) [Up](#) [Previous](#) [Contents](#) [Index](#)

Next: [Saturated boiling heat transfer](#) **Up:** [Flow boiling heat transfer](#)
Previous: [Single-phase heat transfer](#) [Contents](#) [Index](#)

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[Next](#)
[Up](#)
[Previous](#)
[Contents](#)

Next: [Bubble Growth and Nucleate](#) Up: [POOL BOILING](#) Previous: [POOL BOILING](#)

5.1. Bubble Nucleation and Onset of Nucleate Boiling

Vapor may form from a liquid (a) at a vapor-liquid interface away from surfaces, (b) in the bulk of the liquid due to density fluctuations, or (c) at a solid surface with pre-existing vapor or gas pockets. In each situation one can observe the departure from a stable or a metastable state of equilibrium. The first physical situation can occur at a planar interface when the liquid temperature is fractionally increased above the saturation temperature of the vapor at the vapor pressure in the gas or vapor region. Thus, the liquid "evaporates" into the vapor because its temperature is maintained at a temperature minimally higher than its vapor "saturation" temperature at the vapor system pressure. Evaporation is the term commonly used to describe such a situation which can also be described on a microscopic level as the imbalance between molecular fluxes at these two distinctly different temperatures. We consider this conceptual picture again, when condensation is later considered in Section 9.

When considering the other two situations of vapor formation, a vapor bubble or "nucleus" must be formed and be mechanically and thermally stable. Consider the simplest case of a spherical vapor bubble of pressure, P_g , with a saturation temperature of T_g in its liquid with pressure, P_f , which corresponds to its saturation temperature T_{sat} . Mechanical equilibrium requires that

$$P_g - P_f = \frac{2\sigma}{r} \quad (5.1)$$

where σ is the interfacial surface tension and r is the bubble radius of curvature. If the liquid is also in thermal equilibrium with the vapor, $T_g = T_f$, which then implies $T_f > T_{sat}$. If one uses simple thermodynamics, combining equation 5.1 with the equality of local temperatures, one finds the needed liquid superheat ($T_f - T_{sat}$) for the vapor bubble to exist

$$\Delta T = (T_f - T_{sat}) = \frac{RT_{sat}^2}{v_{fg}P_f} \left(\frac{2\sigma}{r} \right) \quad (5.2)$$

One can now relate the superheat required within the bulk of the liquid or at a solid-gas-liquid interface to the size of nuclei.

In a bulk liquid, thermal fluctuations always exist as a small but finite cluster of molecules can take on higher than macroscopic average energies (i.e., temperature). As the bulk liquid increases in its superheat these molecule clusters can take on "vapor-like" energies with increasing probability, and possibly form a stable "vapor nucleus." This process of vapor bubble nucleation is referred to as "homogeneous nucleation." One can use a thermodynamics approach to estimate the degree of liquid superheat necessary to form a stable vapor nucleus; e.g., $T_{HN} \sim 0.9T_{crit}$ for atmospheric pressures.

However, a statistical mechanics approach (Blander 1975, Skripov, 1970) provides a more complete picture of the nucleation rate $\left(J \left[\frac{\text{nuclei}}{\text{cm}^3 \cdot \text{sec}} \right] \right)$ as

5

$$J = \lambda N_o \exp(-\Delta G(T_g)/kT_g) \quad (5.3)$$

where λ is the collision frequency

$$\lambda = kT_g/h \quad (5.4)$$

k is the Boltzman's constant, h is Planck's constant and N_o is liquid molecular density $\left[\frac{\text{molec}}{\text{cm}^3}\right]$. ΔG is the free energy of formation for the vapor nucleus of radius, r , given by

$$\Delta G = \frac{16}{3} \frac{\pi \sigma^3}{(P_g - P_f)^2} \quad (5.5)$$

where σ is evaluated at T_g and P_g is the saturation pressure at T_g . As the liquid superheat ($T_g = T_f$) increases, the surface tension decreases and Δp increases. Thus, at a particular T_g the nucleation rate increases markedly and this corresponds to the "homogeneous nucleation" temperature, T_{HN} ; e.g., $T_{HN} \sim 310^\circ\text{C}$ for water at atmospheric pressure, which corresponds to vapor nuclei radii of ~ 1 micron. Such a superheat value for the onset of vapor nucleation is far above experimental observations for water, under commercial applications, thus it is not the primary mode of vapor nucleation, under normal circumstances. Nevertheless, it must be considered as operating conditions change (e.g., pressure) especially for organic liquids.

Finally, consider the situation where a vapor/gas pocket exists near a solid surface in a liquid (Figure 5.3). Container surfaces can provide sites for vapor formation. This third method of vapor generation from pre-existing vapor nuclei is called "heterogeneous nucleation." Examples of such pre-existing nuclei include noncondensable gas bubbles held in an emulsion in the liquid pool or gas/vapor filled cracks or cavities on container surfaces (Figure 5.3). The latter example is probably the most common circumstance for vapor bubble nucleation. In fact, one could derive the required liquid superheat necessary for the case of an ideal cavity of known radius. One finds it is substantially lower than that needed for homogeneous nucleation, because the cavity radius is much larger. Thus, the bubble requires less superheat and associated pressure difference for thermal and mechanical stability. It is hypothesized that the maximum superheat occurs at the throat of any cavity where the radius is smallest for most aqueous fluids with large contact angles. (Note: the contact angle is the angle through the liquid between the solid-liquid interface and the liquid-vapor interface, and depends on liquid-surface chemistry; e.g., water and commercial steel $\sim 50 - 60^\circ$).

Only a small fraction of all cavities become effective sites for vapor nucleation, because one must consider the balance between the required superheat for a cavity of radius, r_c , and the temperature gradient from the wall, T_w , to the bulk liquid at saturation, T_{sat} ; as depicted by Hsu (1962) Figure 5.4 gives a conceptual picture of the model. As the heat flux at the wall is increased, the wall temperature, which is probably representative of the vapor bubble and local liquid temperature, exceeds the saturation temperature. The liquid will locally vaporize and the vapor nuclei in the cavity will grow toward the cavity throat at the heater surface. If one assumes that the liquid temperature gradient from the wall to the bulk is approximately linear, then the requirement for mechanical and thermal stability of a vapor nucleus at the cavity exit is that the whole bubble should be in a liquid region of boundary layer size, δ , where the temperature is at least above a value of T_f which satisfies the equilibrium condition of

(6)

equation 5.2, for $\delta \sim r_c$. If there is a sufficiently large array of cavity sizes this "onset of nucleation" will first occur when the liquid temperature profile is tangent to the line of thermal and mechanical equilibrium (Figure 5.4). One can algebraically eliminate the cavity radius, r_c , from the two equations by equality of temperature and slope and find the relation between the heat flux, $q_{ONB} = (T_w - T_{sat})$, at which the "onset of nucleate boiling", ONB, occurs

$$(T_w - T_{sat})_{ONB} = \left[\frac{8\sigma q_{ONB} T_{sat}}{i_{fg} h_{fg} \rho_g} \right]^{1/2} \quad (5.6)$$

where all properties are evaluated at $T_{sat}(P_f)$. Now if there are no cavities at this size the heat flux must increase so that the superheat temperature increases to a point where a cavity first exists and the temperature profile intersects the equilibrium curve in Figure 5.4.

One should notice that this model only provides a stability line where the "onset of nucleate boiling" may first occur. To find the particular heat flux and superheat pair one must look for the intersection of this stability line with natural convection mode of heat transfer that would exist prior to boiling (Figure 5.5)

$$q'' = h_{NC} (T_w - T_{sat}) \quad (5.7)$$

$$\text{where } h_{NC} = \frac{k_f}{L} \cdot 14 (Gr Pr)^{1.3} \quad (5.8)$$

and Gr is the liquid Grashof number for $(T_w - T_{sat})$ and Pr is the liquid Prandtl number. For water at atmospheric pressure this model predicts an "onset of nucleate boiling" for a superheat less than 1°C , which corresponds to a cavity size of about 50 microns. In practice the superheat may be as high as 10°C for very smooth, clean metallic surfaces, which indicates larger cavities were not available on the surface. As a very rough guide (Brown, 1967) aqueous fluids seem to have active sites ;SPMlt; 10 microns, organic ;SPMlt; 5 and cryogens ;SPMlt; 1.5 microns.

[Next](#)
[Up](#)
[Previous](#)
[Contents](#)

Next: [Bubble Growth and Nucleate](#) **Up:** [POOL BOILING](#) **Previous:** [POOL BOILING](#)

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